Waves, Currents, & Bathymetric Evolution Near Inlets

Britt Raubenheimer
Woods Hole Oceanographic Institution, MS12
Woods Hole, MA 02543
phone: (508) 289-3427 fax: (508) 457-2194 email: britt@whoi.edu

Steve Elgar
Woods Hole Oceanographic Institution, MS11
Woods Hole, MA 02543
phone: (508) 289-3614 fax: (508) 457-2194 email: elgar@whoi.edu

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LONG-TERM GOALS

The long-term objective is to develop field-verified models for the wave fields, circulation patterns, and morphological evolution near inlets.

OBJECTIVES

The primary objective of our studies in FY13 was to develop, test, and improve models for nearshore processes near and within inlet channels.

In addition, we continued analysis of our Skagit tidal flats measurements, compared observations with numerical simulations of waves propagating across the shallow, muddy, Louisiana continental shelf, estimated surfzone vorticity and short-crested breaking waves (with David Clark), and investigated the evolution of rip currents and the associated bathymetric channels.

APPROACH

Our approach is to collect field observations to test existing hypotheses, to discover new phenomena, to provide ground truth for remote sensing studies, to initialize and test data assimilative models that invert for bathymetry, and to calibrate, evaluate, and improve models for inlet hydrodynamics and morphological evolution.

WORK COMPLETED

i) New River Inlet
Waves and current sensors were deployed at 32 locations near New River Inlet from April 27 through June 1, 2012 (Fig. 1). The data have undergone extensive quality control and are available on the WWW. The effects of waves on the along-channel momentum balance have been evaluated, and the

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results have been presented at several meetings (including AGU and Coastal Dynamics), and a manuscript has been submitted (Wargula *et al.* 2013). The data also are being used in collaboration with other ONR team members and colleagues to evaluate numerical model simulations (Chen *et al.* 2012), propagation of sea level fluctuations (MacMahan *et al.* 2013), dye dispersion and transport (Feddersen *et al.* 2013), and remotely sensed observations (Jessup *et al.* 2012).

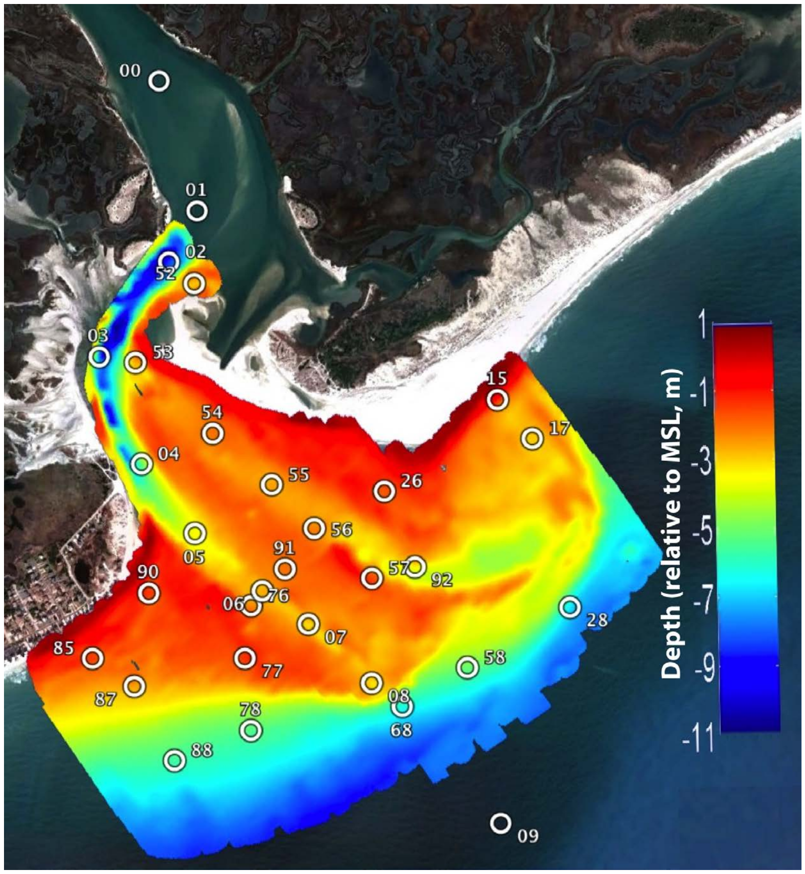

Figure 1. Array of in situ wave and current sensors (white circles) deployed at New River Inlet, spring 2012. The color contours are water depth (Provided by J. McNinch). [Instruments are located across the ebb shoal and to about 2 km up the inlet channel in depths from 1 to 10 m].

(ii) Katama Inlet

A numerical model for the water levels and flows in a two-inlet system was developed (Orescanin *et al*. 2013) based on the momentum and continuity equations. Predictions of the currents observed in Katama Inlet are more accurate when wave forcing is included than when waves are ignored. During Hurricanes Irene and Sandy, when incident (12-m water depth) significant wave heights were greater than 5 m, breaking-wave cross-shore (along-inlet-channel) radiation stress gradients enhanced flows from the ocean into the bay during flood tides, and reduced (almost to zero during Irene) flows out of the bay during ebb tides.

iii) Circulation on Tidal Flats

Analysis of observations collected on the Skagit tidal flats has been completed. The stratification on the tidal flats was generated primarily by tidal straining (owing to the vertically sheared velocity

profile acting on the horizontal density gradient), whereas mixing was the primary mechanism destroying stratification (Pavel *et al*. 2012). Temporal changes in the stratification in the middle of the flats also resulted from advection along and across the flats. The flows and morphological evolution on the Skagit flats have been compared and contrasted with those on the Willapa flats (Nittrouer *et al.* 2013), and the results from the DRI team have been compiled in a special issue of *Continental Shelf Research.*

iv) Wave propagation over muddy seafloors
Waves propagating across a shallow, muddy continental shelf undergo strong dissipation. The dissipative processes result in less generation of high frequency "sea" waves than predicted by models of waves over sandy seafloors. In some cases these models predict increasing wave energy owing to generation by wind, whereas the observations indicate decreasing energy, presumably owing to mud-induced dissipation (Englestad *et al.* 2013).

(v) Vorticity
Eddies and vortices associated with breaking waves rapidly disperse pollution, nutrients, and terrestrial material along the coast. Observations from a novel ring of sensors was used to show that individual short-crested breaking waves generate significant vorticity in the surfzone, and transfer energy from incident waves to lower frequency rotational motions that are a primary mechanism for dispersion near the shoreline (Clark *et al.* 2012).

(v) Rip Currents
A new method was developed to obtain temporally dense maps of bathymetry by updating a spatially dense initial survey with the bathymetric change (e.g., erosion and accretion) estimated from a spatially sparse array of continuously measuring altimeters (Moulton *et al.* 2013). Maps produced by this update method are more accurate than maps obtained by spatially interpolating the sparse altimeter measurements at any given time. The resulting high temporal resolution bathymetric estimates suggest the observed alongshore movement of a rip current may have been caused by migration of the channel, and that there may be tidal fluctuations in the cross-shore location of a sandbar.

RESULTS

Observations of waves, flows, and water levels (Figs. 1 and 2) collected for a month in and near the long, narrow, shallow (~ 3000 m long, 1000 m wide, and 5 m deep), well-mixed New River inlet were used to evaluate the subtidal (periods > 30 hrs) along-inlet momentum balance.

The hydrodynamics and morphodynamics of tidal inlets have been studied for many years. However, most studies have neglected the effects of waves. Numerical model simulations incorporating surface gravity waves indicate that wave forcing may play a significant role in inlet circulation. Model results suggest cross-shore radiation stress gradients owing to dissipation as waves propagate across the ebb shoal can drive fluxes into an inlet (Bertin *et al.* 2009). Alongshore inhomogeneous forcing is predicted to arise from refraction owing to the inlet jet and the alongshore-inhomogeneous bathymetry. In addition, models suggest that tidal prism and bay water levels may be increased as a result of wave forcing (Malhadas *et al.* 2009). This increase in bay water levels can result in enhanced ebb flows from the bay (Olabarrieta *et al.* 2011). However, there are few observational studies to verify these predictions.

Similar to prior observations in curved channels, during flood the maximum flows at New River inlet were approximately centered in the primary channel, whereas during ebb the strongest flows were adjacent to the southwestern shore. During the flood, water funneled into the mouth with weak, fairly uniform magnitude across the inlet width, converging as the inlet width narrowed (Fig. 2), consistent with theory (Stommel and Farmer 1952). The converging flows led to rapid flood flow accelerations near the mouth of the inlet. During the ebb, water left the inlet mouth in two distinct jets, one in the deep channel and the other in the shallower remnant channel across the ebb shoal, with nearly constant flow magnitudes across the ebb shoal. The principal axes differ between flood and ebb, and along the inlet (cross-shore), as well as across the inlet width. Near the inlet mouth the major axis flow direction varies from about -30° to -60°, depending on tidal stage and location. Despite these variations in flow directions, the subtidal momentum balance results are not sensitive to the definition of the along-inlet direction for $-60° < \theta < -15°$ (Wargula *et al.* 2013).

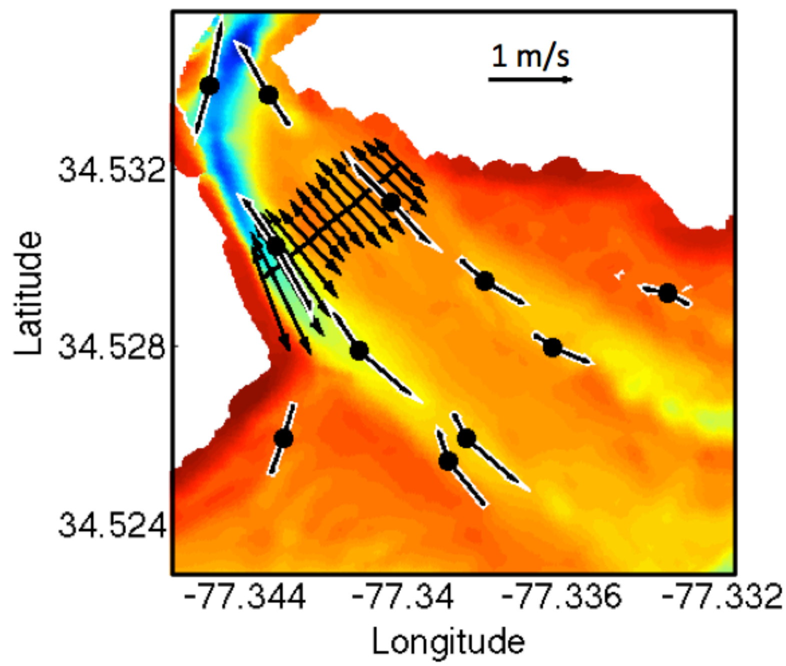

Figure 2. Plan view of New River Inlet. Colors are water depth contours (see Fig. 1 for color scale) and arrows are principal axes for flood and ebb flows. The length of each arrow is the average flood or ebb magnitude (a 1 m/s scale arrow is shown near the top center). Black arrows highlighted in white are calculated from in situ sensors located at the corresponding black circle. Black arrows without white highlighting are calculated from 30-m binned boat-mounted current profiles along the black line across the inlet. [Principal flows magnitudes (ranging from 0.5 to 1.2 m/s) and directions depend on tidal stage and location within the inlet].

Between the offshore and the deep channel locations (sensors 68 and 04 in Fig. 1), subtidal bottom stress is primarily balanced by subtidal pressure gradients ($r^2 = 0.96 \pm 0.02$, Fig. 3b), similar to the tidal balance expected in the straits of long-narrow inlets (Hench *et al.* 2002). Wave forcing is an order of magnitude smaller than the pressure gradient and does not improve the overall balance significantly when summed with the pressure gradient (compare $r^2 = 0.98 \pm 0.01$, Fig. 3c, with $r^2 = 0.96 \pm 0.02$, Fig. 3b), although the standard deviations in each bin are reduced. However, even though wave forcing

usually was relatively small, during big wave events the radiation-stress gradient term became larger than the pressure gradient (see black arrows indicating nor'easter and tropical storm Alberto, Fig. 4), and was needed to balance the bottom stress (Fig. 4b).

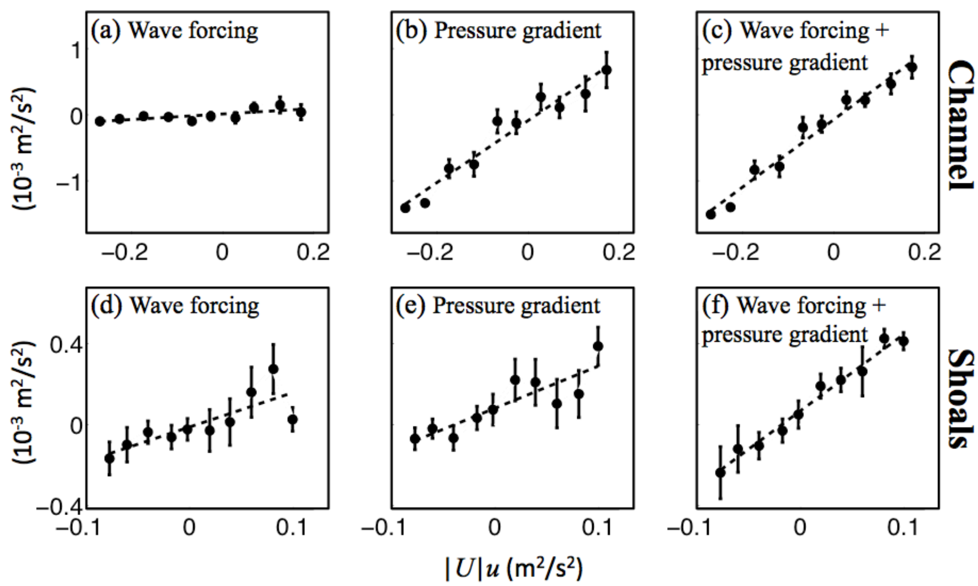

Figure 3. Binned means (circles) and standard deviations (vertical bars) of along-inlet (a, d) wave radiation-stress gradients, (b, e) pressure gradients, and (c, f) sum of along-inlet wave radiation-stress and pressure gradients versus inlet flow ($u|U|$) in the channel (a-c) and on the shoals (d-f). Dashed lines are least squares linear fits to the binned values. The vertical ranges are larger for the channel (a-c) than for the shoals (d-f). [Forcing terms are well correlated with the inlet flows. The magnitude of the wave forcing is small in the channel, but significant on the shoals].

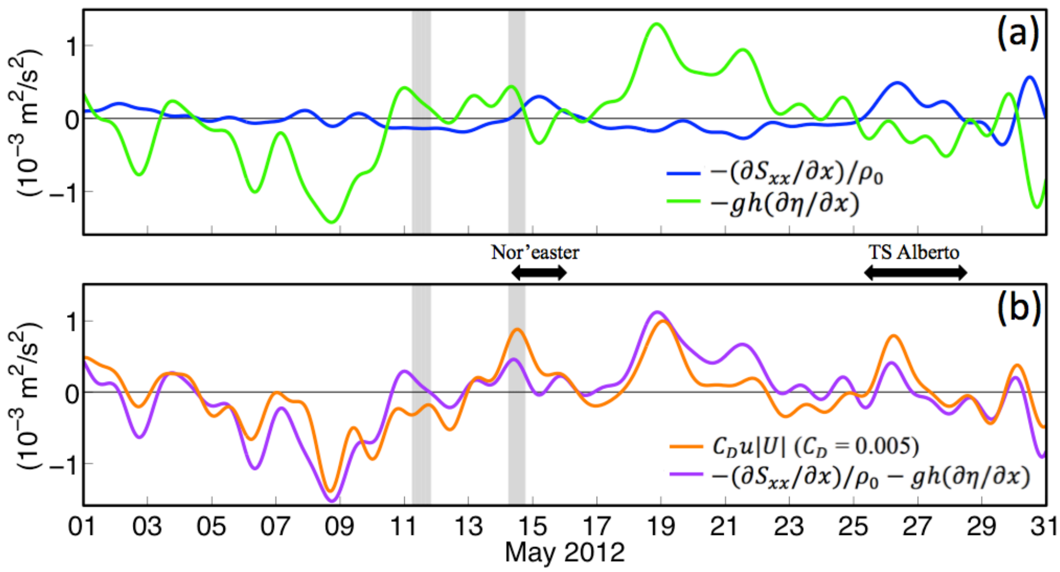

Figure 4. Subtidal, de-meaned channel (a) wave forcing (blue curve) and pressure gradient (green curve) and (b) bottom stress (orange curve, $C_D = 0.005$, from Fig. 3c) and wave radiation-stress plus pressure gradients (purple curve) versus time. The two curves in (b) are correlated ($r^2 \sim 0.7$) at 95% confidence levels. Gray vertical stripes are times of cross-inlet transects (black line, Fig. 2) with the boat-mounted current profiler. Times of a nor'easter and tropical storm Alberto are indicated with black arrows. [The magnitude of wave forcing is smaller than the pressure gradient forcing, except during storms. The sum of wave and pressure forcing is balanced by the bottom stress.]

Between the offshore and shallow shoals sites (sensors 68 and 54 in Fig. 1), wave radiation-stress and pressure gradients have similar magnitudes (Figs. 3d-e and Fig. 5a) and are well correlated with bottom stress ($r^2 = 0.65 \pm 0.13$, Fig. 3d, and $r^2 = 0.75 \pm 0.10$, Fig. 3e). Including both terms improves the correlation between forcing and bottom stress significantly ($r^2 = 0.98 \pm 0.01$, Fig. 3f).

During storms (black arrows at May 15 and May 25-27 in Figs. 4b and 5b), the wave forcing term enhances the flood flows into the inlet (bottom stress is positive) in the channel and on the shoals against an adverse (negative) pressure gradient. The tidally averaged discharge (not shown) measured by the boat-mounted current profiler across the inlet width (black line, Fig. 2) supports the result that wave forcing enhances flood flows. On May 11, during calm conditions ($H_{sig} = 0.5$ m and light northerly winds), the residual discharge was out of the inlet (ebbing). However, on May 14, during an approaching storm ($H_{sig} = 1.0$ m and southerly winds), the residual discharge was into the inlet (flooding). Note that the subtidal pressure gradient was similar on both days (green curves in Figs. 4a and 5a).

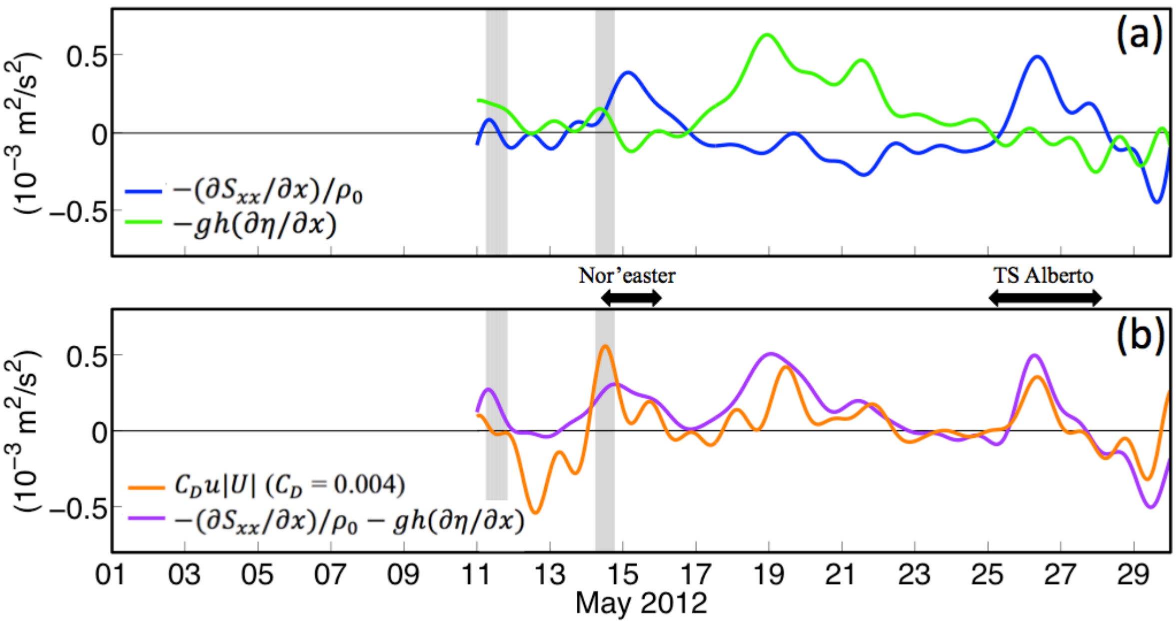

Figure 5. Subtidal, de-meaned shoals (a) wave forcing (blue curve) and pressure gradient (green curve) and (b) bottom stress (orange curve, $C_D = 0.004$, from Fig. 3f) and wave radiation-stress plus pressure gradients (purple curve) versus time. The two curves in (b) are correlated ($r^2 \sim 0.45$) at 95% confidence levels. Gray vertical stripes are times of cross-inlet transects (black line, Fig. 2) with the boat-mounted current profiler. Times of a nor'easter and tropical storm Alberto are indicated with black arrows. [The magnitudes of wave and pressure gradient forcing are similar on the shoals. The sum of wave and pressure forcing is balanced by the bottom stress.]

These observation-based estimates of wave-enhanced onshore (flood) flows are consistent with prior model simulations at Óbidos Inlet and Lagoon, Portugal (Bertin *et al.* 2009; Malhadas *et al.* 2009). In contrast, wave forcing may intensify the ebb jet in the main channel in the inlet at Willapa Bay, WA, USA (Olabarrieta *et al.* 2011). The differences in wave effects for these studies could be owing to differences in geometry of the systems. Willapa Bay (area ~ 260 km^2) is a closed system with a large inlet (width about 10 km and depth up to 24 m), and thus wave forced fluxes into the inlet may cause a rapid increase in mean sea level in the estuary (a 12% increase in tidal prism during a storm was reported [Olabarrieta *et al.* 2011]), resulting in enhanced offshore-directed pressure gradients. Óbidos lagoon (area ~ 7 km^2) also is a closed system. However, the inlet is narrow (~ 25 m) and shallow (~ 1m) (Malhadas *et al.* 2009), possibly restricting the wave-driven flux of water into the lagoon and increasing the time needed for development of an adverse pressure gradient large enough to balance the wave forcing. New River Inlet is an open system, connected to two other inlets via the intracoastal waterway (not shown). These additional inlets allow for water mass exchange and leakage. Thus, wave forcing during storms may enhance flood flows without significant influence on the bay water levels.

IMPACT/APPLICATIONS

Results from New River Inlet suggest that offshore waves can have a strong influence on currents and circulation near and within the inlet channel.

Field observations in a range of nearshore environments have been used to test and improve model predictions for waves, circulation, and morphological change, as well as to provide ground truth for remote sensing of littoral areas and to initialize and test models that invert for the underlying bathymetry.

RELATED PROJECTS

Our observations on the tidal flat are part of a larger effort to investigate and model physical, geological, and morphological processes on tidal flats. As part of the Tidal Flats DRI we have provided bathymetric surveys to all DRI team members, and ground truth (currents, water temperature, salinity) to colleagues conducting numerical model simulations and investigating remote sensing techniques.

The observations of mud-induced dissipation of surface-gravity waves are part of a study that includes colleagues from several other institutions. Our spatially dense observations of waves and currents were part of a larger array of wave sensors spanning many km of the continental shelf, and part of an array that included intensely instrumented tripods with sensors to measure the lutocline and mud properties.

The observations of waves and currents near New River Inlet are being used as ground truth for remote sensing studies (MURI colleagues), to test and improve models for wave propagation, circulation, and morphological evolution, and to initialize and test models that invert for the underlying bathymetry.

Many investigators are using our observational databases to test components of models (eg, the NOPP nearshore community model, DELFT3D, nonlinear wave propagation schemes) for nearshore waves, currents, and bathymetry, and as ground truth for remote sensing studies. More than 100 scientists, engineers, postdoctoral researchers, and students, have accessed our data distribution WWW site [http://science.whoi.edu/users/elgar/main.html] since 2006 to download time series and processed data products for their studies. In FY12 at least four journal papers used data we gathered in Duck, NC in 1994 (!), and more than 20 people (including investigators from U.S. and international universities, government and DoD laboratories, and private companies) downloaded data from the Duck94, SandyDuck, NCEX, SWASHX, WORMSEX, STIFEX, and RIVET1 projects.

Some of the work discussed here was in collaboration with Dr. Elgar's NSSEFF project to study morphological evolution in littoral areas.

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HONORS/AWARDS/PRIZES

Britt Raubenheimer, Woods Hole Oceanographic Institution, Doherty Education Chair, Woods Hole Oceanographic Institution.

Melissa Moulton, Steve Elgar, Britt Raubenheimer, Woods Hole Oceanographic Institution, Best Student Paper, Coastal Dynamics conference.

Steve Elgar, Woods Hole Oceanographic Institution, appointed to Outer Continental Shelf Science Committee, Bureau of Ocean Energy Management, Deptartment of Interior (officer, parliamentarian).